Performance Analysis of a Hybrid Opto-Electronic Packet Switch using WDM Technology

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***Abstract*—We investigate the performance of a hybrid opto-electronic switch where the connected azimuths support WDM channels, taking into account different packet classes. A compromise is discussed between the energy savings and the performance improvement given by using shared wavelength converters.**

***Keywords*—Optical packet switching; Optoelectronic devices; contention resolution; switching energy consumption.**

I. Introduction

Wired signals transmissions are almost always carried on optical fibers at a relatively low energy per bit. Logically, switching should be also ensured optically, however, due to the lack of practical all-optical buffering solutions, all-optical packet switches are extremely vulnerable to contention and lead to high Packet Loss Rates (PLR) even at unrealistically low loads [1]. That's why switching is still performed electronically. The numerous required Optical-Electrical-Optical (O-E-O) conversions make the switching one of the areas with the fastest-growing power consumption [2].

Curbing the energy consumption is an important challenge for future optical networks. A way to do so is to think about different switching technologies. Therefore, a hybrid opto-electronic switch was proposed [3] and demonstrated [4], [5]. It consists of an optical switching matrix supplemented with a shared electronic buffer that stores packets in case of contention.

An analysis of a hybrid opto-electronic switch [6] using simulations and an Engset-type analytical model shows performance improvements in terms of PLR and sustainable load (ρ) compared to the all-optical case. This was confirmed by the performance analysis [7] that takes into account different classes of service. In addition, the reduction of O-E-O conversions compared to an all-electronic switch indicates that the hybrid switch is a potential solution to the energy consumption.

In the analyses cited above, the azimuths connected to the switch were supposed to support interchangeable channels, such as parallel optical fibers in the same cable or Space Division Multiplexed (SDM) multi-core or multi-mode fibers. In the current investigation, we consider WDM channels, which are much more flexible and efficient, hence widely used, but do not satisfy the interchangeability condition and lead to higher PLR [8]. First, section II describes our switch architecture and the switching policy that we established in order to satisfy the constraints of each packets class. Second, we present in section III our simulation results that prove the need of wavelength (λ) converters to improve the switch performance. However, since λ converters themselves consume power, we discuss in section IV if their consumption negate the energy savings achieved by the hybrid switch compared to all-electronic switches.

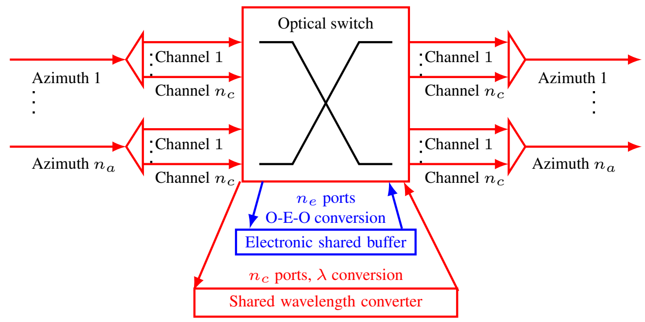

Fig. 1. Hybrid switch architecture

II. Architecture and Switching Policy

The main parameters to dimension the hybrid switch are: the number of connected bidirectional azimuths (n_a), the number of supported WDM channels per azimuth in each direction (n_c) and the number of electronic input as well as output ports to the buffer (n_e). The switch can also have $n_{\lambda cv}$ shared λ converters. Fig. 1 presents the switch architecture where $n_{\lambda cv} = 1$. We opt for shared converters instead of one converter per azimuth such as in [9] since they are energetically costly [10]. The number of maximum simultaneous conversions per converter and the number of each converter input as well as output ports is n_c. We assume that conversions are possible from any λ to any available λ. Within this assumption, that can't be satisfied by current all-optical λ converters, we may consider that a wavelength conversion consumes energy as an O-E conversion. We assume also that the λ converters work in a cut-through mode: a conversion starts before the whole packet has been received by the converter.

The packet classification has been chosen from realistic assessments: Reliable (R), Fast (F) and Default (D) packets respectively make up 10, 40 and 50% of the global traffic [11]. They may respectively refer to digital data and file transfer packets, voice and interactive video packets, and other types of packets. R packets must reach their destinations without loss, but they are the lowest priority packets in terms of latency. F packets have the highest priority regarding the latency, but they are more tolerant than R packets regarding the PLR. D packets are least restrictive with respect to both PLR and latency.

The switching strategy is established in order to meet each service's class constraints. At the reception of a packet, the

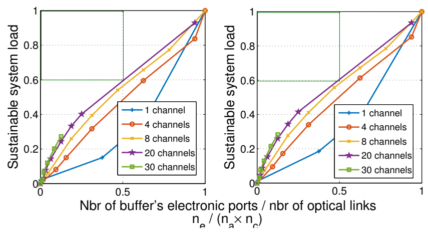

Fig. 2. Sustainable ρ vs $n_e/(n_a \times n_c)$, $n_a = 8$, Left: at $\mathrm{PLR_D} = 10^{-4}$, Right: at $\mathrm{PLR_F} = 10^{-4}$

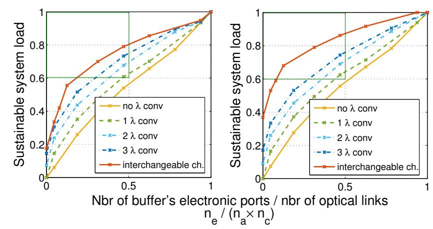

Fig. 3. Sustainable ρ vs $n_e/(n_a \times n_c)$, Left: at $\mathrm{PLR_D} = 10^{-4}$, Right: at $\mathrm{PLR_F} = 10^{-4}$, $n_a = 8$, $n_c = 8$, with shared λ converters

switch checks whether the corresponding channel to its egress azimuth (same λ) is available. If yes, the packet is directly sent on its way over it. Else, the switch tries to send it through another channel on a converted λ. Otherwise, if an electronic input port is available, the packet is buffered and then re-emitted whenever a channel is released and an output electronic port is available. Otherwise, depending on the packet class, there is a preemption policy: if the newly-arrived packet is of type R, the switch may interrupt the last (preferably D, or F) packet being sent to the buffer or the last (preferably D, or F) packet being sent to the same egress azimuth and send the R packet preferentially. Otherwise, if the newly-arrived packet is of type F, the switch checks if there is a D packet being sent to the same azimuth to preempt it and send the F one instead. In the worst case, in the absence of any of the possibilities listed above, the packet is dropped.

III. Need for Wavelength Converters

In our simulations, we considered a fixed packet duration of $\sigma = 10$ µs, which represents about 100 kbit for standard 10 Gbit/s systems. It may correspond to a jumbo Ethernet frame or an aggregation of several IP packets [6]. The hybrid switch works in asynchronous mode and the packet inter-arrivals are randomly generated. Given this assumption, our study is equivalent to the case of having variable σ, but with a mean duration of 10 µs. Fig. 2 shows the evolution of the sustainable load ρ at $\mathrm{PLR_D} = 10^{-4}$ and $\mathrm{PLR_F} = 10^{-4}$ as a function of the ratio between the number of the shared buffer's ports (n_e) and the number of optical links ($n_a \times n_c$ which corresponds to an all-electronic switch ports) for a degree-8 hybrid switch ($n_a = 8$) with WDM channels and no λ converters. We note that for interactive video packets (F packets), it is recommended that PLR must be $\leq 10^{-2}$ across the network [12]. Assuming paths can cross up to 100 nodes, we take as a reference for a single node $\mathrm{PLR_F} = 10^{-4}$. We also impose the same constraint to $\mathrm{PLR_D}$ even though D packets are more tolerant to the PLR.

The hybrid switch is considered of interest when:

- The sustainable $\rho \geq 0.6$: we consider the load of 60% as a minimum acceptable operating point. This is a widespread reference.
- $n_e \leq (n_a \times n_c)/2$: the buffer must incur significantly less O-E-O conversions than an all-electronic switch of the same size.

Although the hybrid switch with WDM channels improves the sustainable ρ compared to an all-optical bufferless switch ($n_e = 0$), it is not possible to fulfill the two conditions simultaneously. Besides, $\mathrm{PLR_R}$ is not null. Performance is notably lower than in the case of interchangeable channels [7]. Thus, we supplement the switch with $n_{\lambda cv}$ shared wavelength converters. Fig. 3 shows the evolution of the sustainable ρ as a function of $(n_e/[n_a \times n_c])$ where $n_c = 8$ WDM channels and $n_{\lambda cv} = 1, 2$ or 3 converters. In this case, the hybrid switch fulfill the two conditions cited above. For example, with just one converter, the sustainable ρ at $\mathrm{PLR_D}$ and $\mathrm{PLR_F} = 10^{-4}$ are around 60% when $n_e = 30 = 0.47 \times n_a \times n_c$. In addition, the PLR requirement of the R class is satisfied.

We remark that the increase of the sustainable ρ when we add just one converter to the switch, is higher that the additional increase when we add another converter. For example, when $n_e = 12 \simeq 0.2 \times n_a \times n_c$, supplementing the hybrid switch with one wavelength converter increases the sustainable ρ at $\mathrm{PLR_F} = 10^{-4}$ by absolutely 9.4%. Adding a second converter makes an additional increase by 8.3%, and adding a third converter increases ρ with 7.6%. Indeed, the sustainable ρ becomes closer to its maximum in the best case when channels are interchangeable. Moreover, having additional electronic ports is more beneficial than having additional λ converter ports. Considering the same example ($n_a = 8, n_c = 8, n_e = 12$), adding a wavelength converter with 8 ports increases the sustainable load at $\mathrm{PLR_F} = 10^{-4}$ by 9.4%, while having 8 more buffer's electronic ports leads to an increase by 12.2%.

Considering the delay criterion, Fig. 4 shows its evolution for each class of service versus ρ for the example of $(n_a, n_c, n_e) = (8, 8, 30)$. The delays in the case of WDM channels are greater (6 µs at a system load of 70%) than interchangeable channels (2 µs) since more packets need to be buffered. However, all the delays are less than $\sim$ 10 µs, with 4 orders of magnitude below acceptable limits even for Fast packets, that require no more than 150 ms one-way end-to-end delay. In addition, thanks to the switching strategy, supplementing the hybrid switch with λ converters decreases the delays. In fact, a λ conversion is preferred than buffering a packet.

IV. Still Saves Energy?

Supplementing the hybrid switch with λ converters in the case of WDM channels reduces the PLRs and the delays. However, these converters themselves consume power and may negate the energy savings achieved by the hybrid switch compared to electronic switches. Since we considered that a λ conversion consumes as much power as an O-E conversion, we will compare the percentage of O-E-O reduction with the

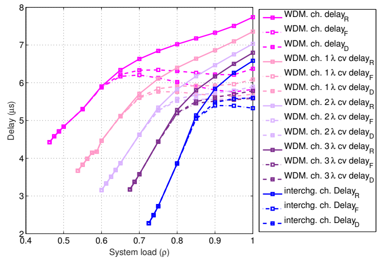

Fig. 4. Delays vs system load, $(n_a, n_c, n_e) = (8, 8, 30)$

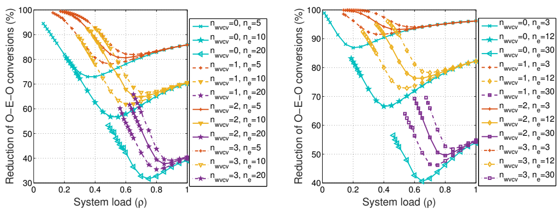

Fig. 5. O-E-O reduction vs ρ, $n_a = 8$, Left: $n_c = 4$, Right: $n_c = 8$

percentage of wavelength conversions. We take as an example a degree-8 hybrid switch with 4 or 8 WDM channels per azimuth.

The O-E-O reduction, reflecting the energy savings versus an all-electronic switch, is expressed as:

$$100\% \times \left(1 - \frac{\text{nbr of buffered packets}}{\text{nbr of all switched packets}}\right) \qquad (1)$$

Fig. 5 presents its evolution as a function of ρ. Compared to an all electronic switch, the hybrid switch does away with at least 58% of O-E-O conversions when $n_c = 4, n_e = 10$ and with at least 40% when $n_c = 8, n_e = 30 \simeq 0.5 \times n_a \times n_c$. Thus, the reduction of energy consumption that could be achieved by the hybrid switch may be very important.

The λ conversion rate is the ratio between the number of packets sent optically to their egress azimuths but on a converted λ and the number of all switched packets. Fig. 6 presents its evolution as a function of ρ. The additional increase of the conversion rate is higher when $n_{\lambda cv}$ passes from 1 to 2, than when it passes from 2 to 3. This explains the evolution of the sustainable ρ increase as a function of the number of additional wavelength converters. For example, for n_c= 4 WDM channels per azimuth, no more than 15% of the packets are λ-converted when the switch has one converter. The maximum rate is 25% when the switch has 2 converters, meaning an additional 10%. If the switch has 3 converters, the maximum conversion rate is equal to 32% with an additional rate of just 7%.

Comparing the rates, when the switch has 8 channels per azimuth and 3 wavelength converters, at $\rho = 0.5$, up to 37% of the switched packets are λ-converted, which is a considerable rate. However, even for this 'poor' example, 50% of the O-E-O conversions are done away with compared to an electronic switch. Thus, considering that a λ conversion consumes the same power as an O-E conversion, the energy consumption of λ converters is lower than the energy saved by the hybrid switch compared to electronic ones.

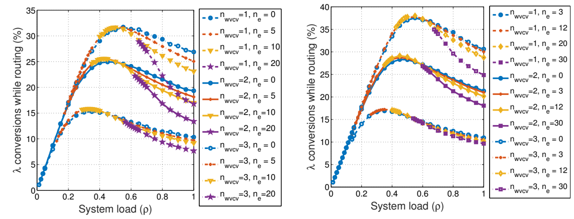

Fig. 6. λ conversions rate vs ρ, $n_a = 8$, Left: $n_c = 4$, Right: $n_c = 8$

V. Conclusion

The investigation of the hybrid switch connected to WDM channels shows the need of λ converters to obtain acceptable PLRs and sustainable system load. Although these converters consume power, the hybrid switch still shows net energy savings compared to electronic ones. However, our simulations show that having additional electronic ports to the buffer leads to lower PLR than having more λ converters ports.
In future work, we will investigate an intermediate case combining SDM with WDM channels such as multicore fibers where each core supports different wavelengths. This vision may be a compromise between the capacity increase thanks to WDM and the performance improvements thanks to the interchangeability wherever SDM employment could be possible.

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